A SEARCH FOR CYCLOTRON RESONANCE FEATURES WITH *INTEGRAL*

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ABSTRACT

We present an *INTEGRAL* observation of the Cen-Crux region in order to search the electron cyclotron resonance scattering features from the X-ray binary pulsars. During the AO1 200 ks observation, we clearly detected 4 bright X-ray binaries, 1 Seyfert Galaxy, and 4 new sources in the field of view. Especially from GX301-2, the cyclotron resonance feature is detected at about $\sim$ 37 keV, and width of 3–4 keV. In addition, the depth of the resonance feature strongly depends on the X-ray luminosity. This is the first detection of luminosity dependence of the resonance depth. The well-known twin pulsars are spatially separated by JEM-X and IBIS/ISGRI, and pulse periods are measured individually; 296.90 sec for 1E1145-6141 and 292.5 sec for 4U1145-619. The cyclotron resonance feature is marginally detected from 1E1145.1-6141. Cen X-3 was very dim during the observation and poor statistics disable us to detect the resonance features.

Key words: X-rays; High mass X-ray binary pulsar; cyclotron resonance feature.

1. INTRODUCTION

Neutron stars (NS) are regarded as having extremely strong magnetic fields (MFs) reaching 10^{12-13} G. Nevertheless, the origin and evolution of such strong MFs have been standing as a long mystery. The electron cyclotron resonance scattering features (CRSFs) in the X-ray spectrum are the only direct method to measure the MFs on the NS. The center $E_{\rm c}$ of CRSF in their spectra reflects the magnetic field B, given as $E_{\rm c} = 11.6 \times (B/10^{12}G \times (1+z)^{-1}{\rm keV}$. In early 1990's, *Ginga* (Japanese 3rd X-ray satellite) provided a powerful mean to search for CRSFs in the 2–30 keV range in the X-ray binary pulsars (XBPs) spectra. In addition to two already known XBPs, new CRSFs were discovered from more than 6 XBPs. The MF strength of XBPs seems to be concentrated in a narrow range of B= (1–5) $\times$ 10^{12} G (Makishima et al. 1999). However, the high-field side of the distribution, although augmented by *SAX* and *RXTE*, is still subject to considerable selection effects. *INTEGRAL*, with its wide dynamic range and good sensitivity, is expected to be very powerful to search for the CRSF at higher energy range. Here we report the *INTEGRAL* observation of 4 Galactic XBPs, in an attempt to detect CRSFs at higher energy range of 10–150 keV.

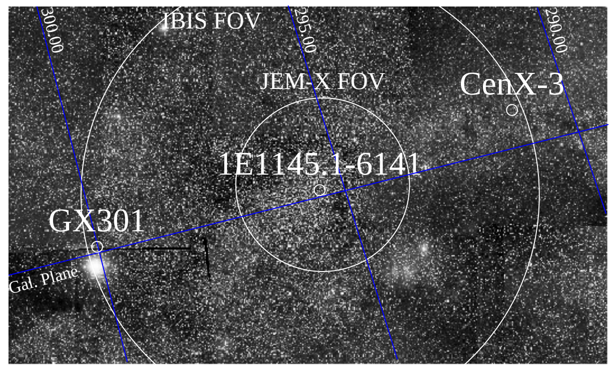

Figure 1. An IBIS and JEM-X fully coded field of view superposed on the DSS image in the Cen-Crux region.

2. OBSERVATION AND DATA REDUCTION

We have observed the Cen-Crux region during the AO1 phase, from the end of June 2003 to the beginning of July 2003, with an exposure time of $\sim$ 200 ksec, which is composed of 52 science window. Cen-Crux region is located on the Galactic plane and 60° apart from the Galactic center, and it is known as a region where the bright X-ray pulsars are concentrated. The observations field of view are centered

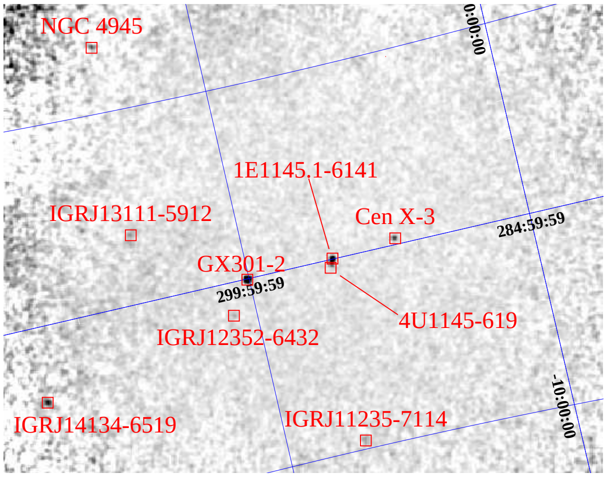

Figure 2. The mosaic image of Cen-Crux region obtained by IBIS/ISGRI in the energy range 15–40 keV. The total exposure time is ∼ 200 ksec.

near 1E1145.1-6141, one of the bright X-ray pulsar, shown in figure 1. Imaging analysis is performed using the current version (3.0) of the Offline Science Analysis (OSA) software. Spectral extraction is performed independently for every science window. The data of IBIS/ISGRI are mainly studied and we also use JEM-X and SPI spectra.

3. HARD X-RAY SOURCE POPULATION IN CEN-CRUX REGION

We generated the significance image of 15–40 keV and 40–100 keV range and search for sources which exceeds 7σ significance in 15–40 keV, this detection limit corresponds to ∼ 5mCrab. As a result, we detected 9 hard X-ray sources in the FOV (fig. 2). As expected, 4 sources are well known XBP; Cen X-3, GX301-2, 1E1145.1-6141, and 4U1145-619. NGC4945, which is one of the brightest Seyfert 2 galaxy in hard X-ray band, is detected in the northeast region. 4 new sources are also discovered in the FOV. The source list is summarized in table 1.

4. GX301-2

The high mass X-ray binary pulsar GX301-2 is a wind-fed neutron star around the supergiant companion Wray 977 (Sato et al. 1986). The pulse period is 675.7 sec (Pravdo et al. 1995) and orbital phase is 41.508 ± 0.007 days (Sato et al. 1986). The CRSF is firstly reported at 35.6± 1.6 keV by *Ginga* (Mihara 1995, Makishima et al. 1999), although the detection is not firmed. A 42.4±3.8 keV CRSF is reported by *RXTE* (Coburn et al. 2002). GX301-2 was very bright (∼ 100mCrab) during the observations, and was clearly detected by JEM-X, IBIS/ISGRI, and SPI.

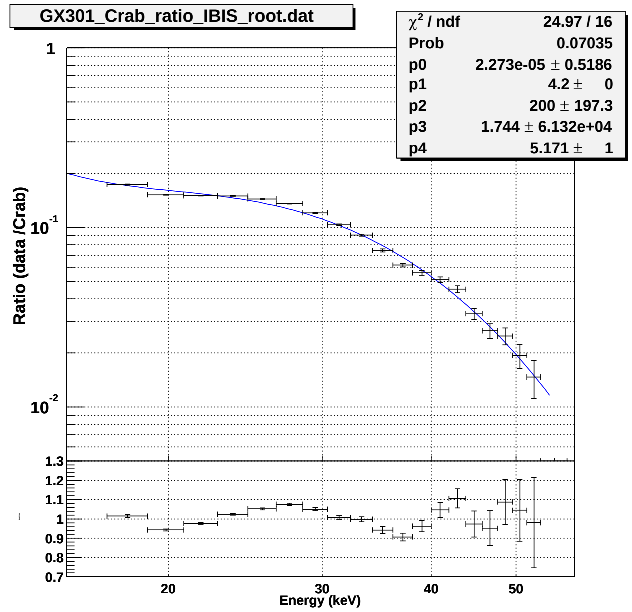

Figure 3. The ISGRI Crab ratio fitting of GX301-2.

4.1. Crab-ratio spectrum

Because the CRSF detection strongly depends on the continuum spectrum, the accuracy of the detector response matrix is very important in the study. However, as reported in Goldwurm et al. 2003, the response matrix of the ISGRI detector is under development. To make the spectrum fitting using the response matrix distributed by Integral Science Data Center (ISDC), a large systematic error, about 10%, is required. That makes our CRSF search difficult. In order to avoid large uncertainty caused by the current response matrix, we firstly try the Crab-ratio spectrum analysis. By dividing our data by the well-known power law spectrum, it becomes free from the complexity of the detector response matrix, and we can directly investigate the CRSFs.

Figure 3 shows the crab-ratio spectrum of ISGRI. We fit the data for the simple continuum and obtained the chi-squared. As shown in the bottom panel, the residual is clearly seen at about 30-40 keV. Therefore we add the CRSF absorption model as an additional component. As a result, CRSF at 36± 1.5 keV is detected, and the detection significance of the CRSF is about 2.1σ. The absolute intensity of the CRSF is not determined, because we used the spectrum ratio.

4.2. Spectrum fitting

Although the response matrix of ISGRI is still under development, we can fit the data by assuming a systematic error of 10%. At first, we evaluate the continuum spectrum using Negative and Positive Exponent (NPEX) model, as

$$F_{\rm NPEX}(E; A_{\rm n}, A_{\rm p}, \alpha, \beta, T) = (A_{\rm n}E^{-\alpha} + A_{\rm p}E^{+\beta}) \cdot exp(-\frac{E}{T}).$$

Table 1. List of sources detected during observations of Cen-Crux region.

Object	RA	Dec	Significance(soft/hard)*	Flux [mCrab]**	Class
GX301–2	186.6587	-62.7752	233.3/16.1	78	XBP
Cen X-3	170.3223	-60.6268	26.2/<3	15	XBP
1E1145.1-6141	176.8983	–61.9977	74.9/26.1	50	XBP
4U1145-619	176.9178	-62.3190	28.5/10.0	37	XBP
NGC4945	196.3826	-49.5000	6.13/ 7.7	30	Seyfert 2
IGRJ14134-6519	213.4368	-65.3282	10.2/3.2	8	?
IGRJ12352-6432	188.8395	-64.5357	8.5/<3	12	?
IGRJ13111-5912	197.8113	-59.2058	7.9/4.5	8	?
IGRJ11235-7114	170.9609	-71.2420	7.0/<3	8	?

* : 15–40 keV for soft , 40–100 keV for hard band respectively.
** : 15–100 keV

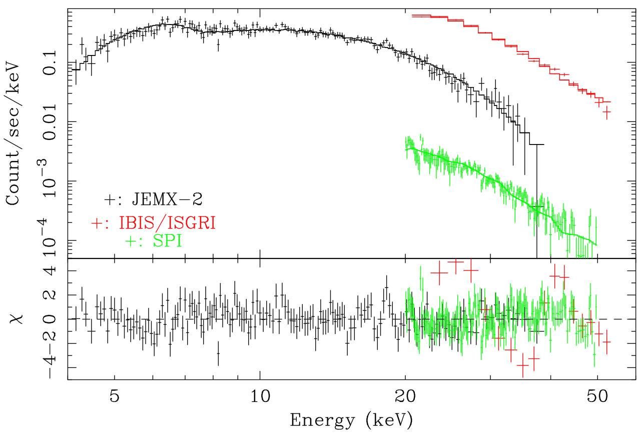

Figure 4. The ISGRI, JEM-X and SPI simultaneous fitting of GX301-2 with a detector response matrix.

where A_n, A_p are normalization and α, β are photon index, T is a cut-off energy and E the photon energy. This model successfully reproduces the subtle curvature change in the binary X-ray pulsar continuum (Makishima et al. 1999, Mihara 1995). We can evaluate the parameters from the fitting and the reduced χ^2 is 2.69 (179 degrees of freedom(d.o.f.)) for JEM-X and IBIS simultaneous fitting. The obtained reduced χ^2 suggests that the single NPEX continuum cannot explain the JEM-X and IBIS spectrum, and we can clearly find an excess of the residual at about $\sim$ 35 keV. Then we add the CRSF model, as

$$F(E) = AE^{-\Gamma} exp\{-\frac{D(WE/E_c)^2}{(E-E_c)^2+W^2}\}$$

where F(E) is photon number at energy E, A is normalization, Γ is photon index, while E_c, D, and W are the energy, depth, and width of the cyclotron resonance line. The exponential factor represents the classical electron cyclotron resonance scattering. After adding the CRSF model into NPEX continuum, the fit is improved and the reduced χ^2 is 1.60 (176 d.o.f.). The energy E_c is 35.6± 0.3 keV and depth D is $1.1^{+0.8}_{-0.1}$.

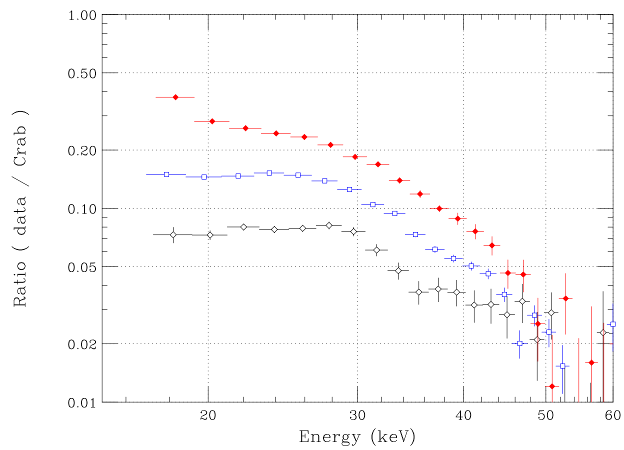

Figure 5. Luminosity dependence of the X-ray spectrum, upper (red) , middle (blue) and bottom plot (black) shows the spectrum which count rate in the range of 15–40 keV is defined as > 20 ph/s/bin, 20 > cps > 10, < 10 ph/s/bin.

4.3. Luminosity dependence of the cyclotron line

Finally, in order to study the luminosity dependence of the CRSF in GX301, we extract the spectra from three different surface brightness separately, which is defined as *cps* >20 count/s, 20> *cps* > 10 counts/s, cps < 10 counts/s, in the energy range of 15–40 keV respectively. Figure 5 shows the spectrum of three different surface brightness. We can clearly see that the depth of the CRSF increases as the luminosity decreases. Because of the low statistics and unreliable response matrix, we do not show more detailed result in figure 5.

5. TWIN PULSARS

1E1145.1-6141 and 4U1145-691 locates very close each other, $\sim$ 20′, and are known as "*twin pulsar*". With *INTEGRAL*, we can spatially separate the sources with JEM-X and possibly IBIS. From 1E1145.1-6141, we marginally find the CRSF at about 20 keV by the Crab-ratio analysis, but the

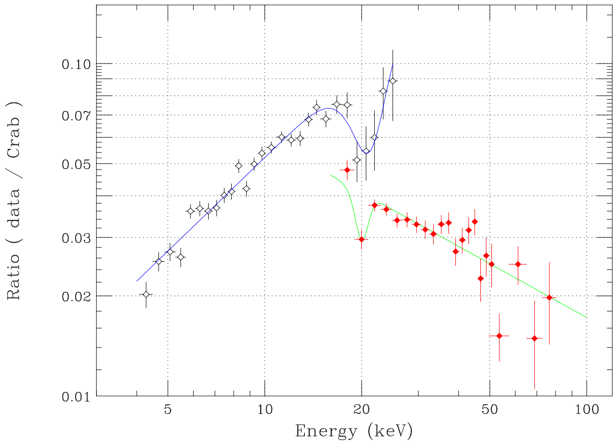

Figure 6. The ISGRI (red/green) and JEM-X (black/blue) Crab ratio fitting of 1E1145.1–6141.

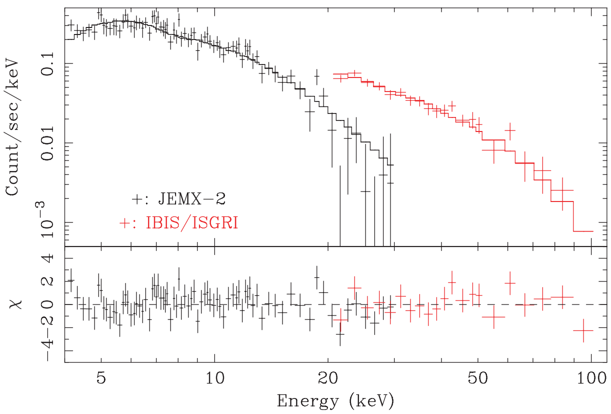

Figure 7. The ISGRI and JEM-X spectrum fitting of 4U1145-619.

detection is still marginal. From H1145-619, CRSF is not detected in the range of 5–80 keV.

6. CEN X-3

One of our primary purpose of Cen X-3 observation is to search for the higher harmonic. However the Cen X-3 was very dim with a flux of $\sim$ 15 mCrab in 15-100 keV energy band. Figure 8 shows the JEM-X, IBIS, and SPI simultaneous fitting of the Cen X-3 observation. The data are successfully reproduced by the NPEX model, but we fail to detect the CRSF at about 20 keV, which is reported by Santangelo et al. 1998. Further deep observation is important.

7. SUMMARY

We observed the Cen-crux region in order to search for the cyclotron resonance scattering features with *INTEGRAL*. During 200 ksec observation, we have detected 4 X-ray binary pulsars. For GX301-2, the CRSF is clearly detected at about $\sim$ 37 keV in

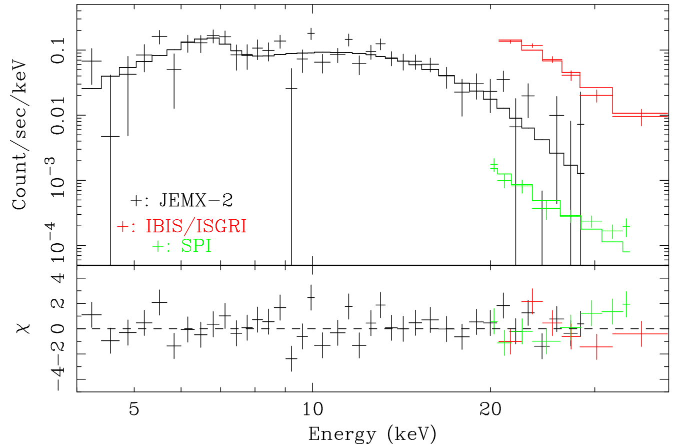

Figure 8. Cen X-3 spectrum fitting with ISGRI, JEM-X and SPI.

the phase averaged spectrum and we found that the depth of the CRSF depends on the X-ray luminosity. The center energy of the CRSF is consistent with the *Ginga* result (Mihara 1995). The *twin pulsar* is spatially separated by JEM-X and IBIS/ISGRI. For 1E1145.1-6141, one of the pulsar twins, we marginally detected the CRSF at about $\sim$ 20 keV. This is a first detection if the data are statistically significant. Cen X-3 was very dim and resultantly the CRSF is not detected significantly. Further detailed analysis is being expected after a new release of OSA.

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